Galactic Cosmic Ray Simulation at the NASA Space Radiation Laboratory in 2021

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2022 NASA Human Research Program Investigators' Workshop
February 7, 2022

*Disclaimer: This work was prepared while Z.S. Patel was employed at KBR/NASA JSC. The opinions expressed in this work are the author's own and do not reflect the view of the National Institutes of Health, the Department of Health and Human Services, or the United States government

Outline

- Introduction
- NSRL GCR Simulator
- Simulation Approaches
- GCRsim Workshop
- Conclusions

Introduction

- Galactic Cosmic Ray Simulator (GCRsim) Workshop held virtually at NASA Langley in December 2020

- Primarily focused on mixed field effects

- **Adverse health effects of space radiation**
  - Cancer
  - Cardiovascular disease
  - Central nervous system decrements

- Radiobiology experiments conducted at the NASA Space Radiation Laboratory (NSRL)
  - Help improve understanding of space radiation health effects

- GCR Simulator provides the shielded deep space environment encountered by astronauts

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Goals of Workshop

- Workshop goals framed as questions
  - **Is there any experimental evidence suggesting that simplifications, modifications, or improvements to the GCRsim beam are needed?**
  - **Does the current GCR beam <u>adequately</u> represent the radiation environment encountered by astronauts in deep space behind shielding?**
  - **What future studies need to be performed to improve the GCRsim mixed field definition?**

GCR Simulator: Development

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- Preliminary GCRsim design considerations focused on
  - Reference field specification
  - Beam selection strategies

- Broad range of mission architectures, shielding configurations, and physical quantities were considered

- **It was determined that a single reference field could be identified for the GCRsim**
  - Doses (Gy) varied by ±3%
  - Dose equivalents (Sv) varied by ±16%
  - Across all radiosensitive tissues and scenarios considered

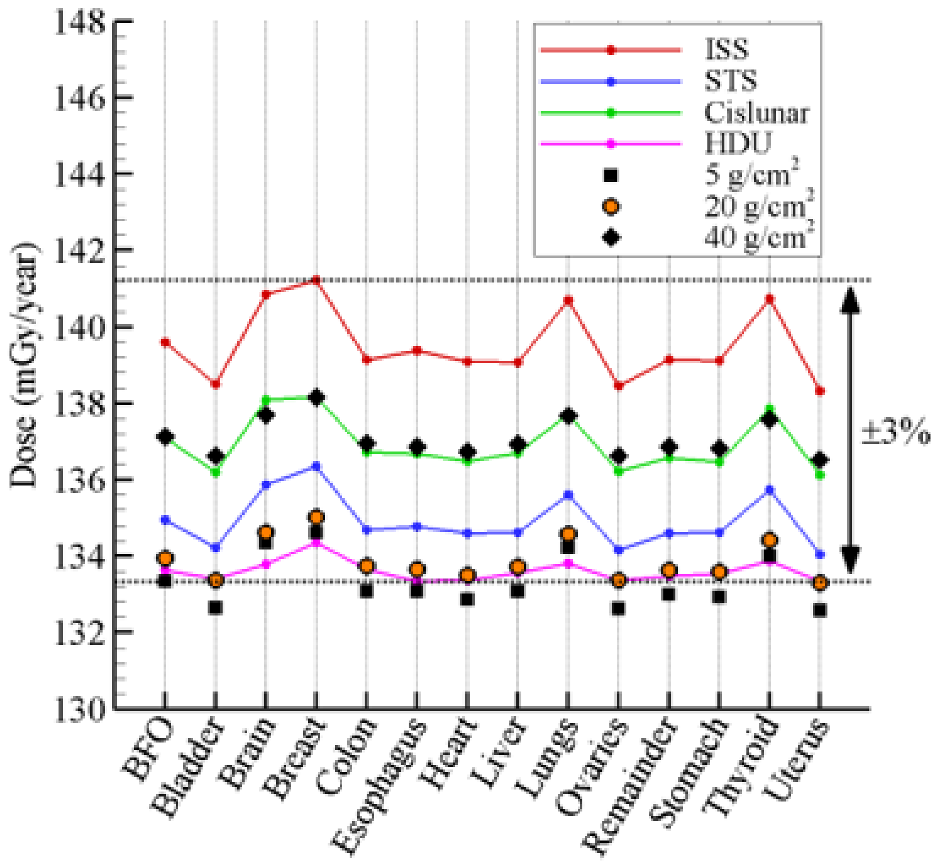

Figure 1: Tissue dose in various shielding configurations

GCR Simulator: Reference Field

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- **GCRsim reference field**
  - Female blood forming organ (BFO) behind 20 g/cm^2 spherical aluminum shielding during solar minimum conditions

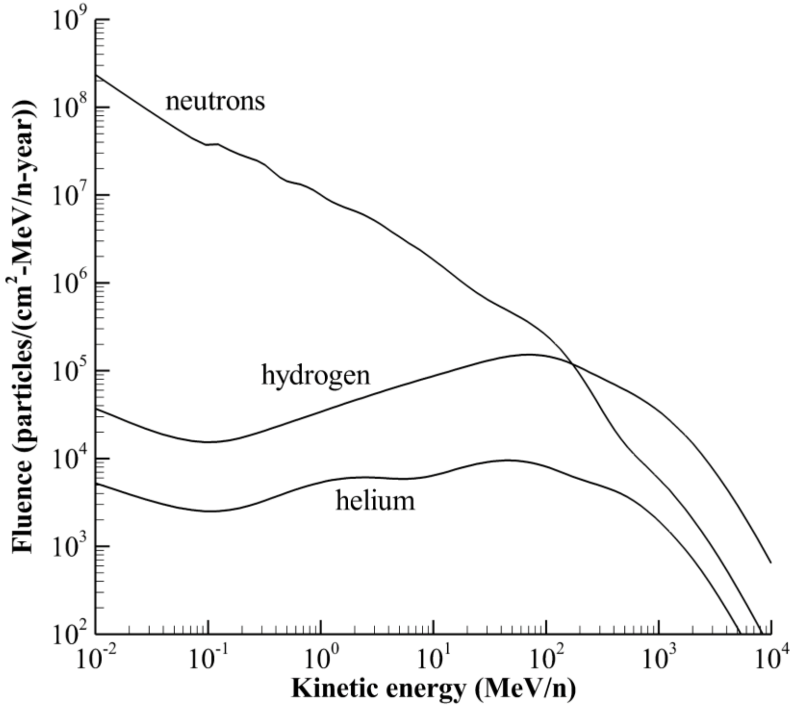

Figure 2: Reference Field Energy Spectra for Neutrons, Hydrogen, and Helium

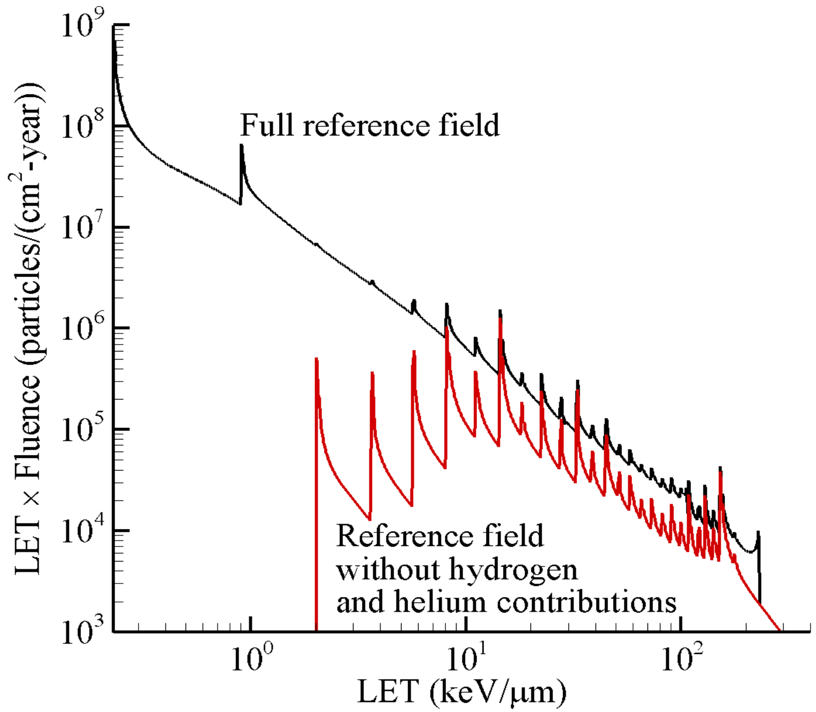

Figure 3: Reference Field LET Spectra with and without Hydrogen and Helium

Table 1: Calculated Annual Field Quantities

	H	He	HZE
Average hits per cell nucleus	126	7	0.5
Dose (mGy)	86.0	22.5	8.9
Dose eq. (mSv)	131.1	93.8	73.3
Average quality factor	1.5	4.2	8.2

GCR Simulator: Beam Definition

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- **33 ion beam - protons, helium, and heavy ions**
  - Heavy ions: ^{12}C, ^{16}O, ^{28}Si, ^{48}Ti, ^{56}Fe
  - Polyethylene degrader system used to generate a lower energy spectrum for ^{1}H and ^{4}He beams
- **Majority of dose in the beam sequence from protons and helium with sporadic heavy ions**
  - 4 ^{1}H energies plus degrader (65-75% of dose)
  - 4 ^{4}He energies plus degrader (10-20% of dose)
  - 5 Heavy Ions (6-8% of dose)
- **<u>Approximately 1 hour to deliver!</u>**

Table 2: GCR Simulator Beam Definition

Ion	Energy (MeV/n)	Range (cm)	LET (keV/µm)	Dose (mGy)
^{1}H	100	*Polyethylene degrader to*		
^{1}H	150	15.9	0.54	35.0
^{1}H	250	38.1	0.39	68.9
^{1}H	1000	326.6	0.22	123.6
^{4}He	100	*Polyethylene degrader to*		
^{4}He	150	16.0	2.17	7.5
^{4}He	250	38.3	1.56	16.4
^{4}He	1000	327.8	0.88	24.9
^{12}C	1000	110.1	7.95	11.7
^{16}O	350	17.0	20.8	15.4
^{28}Si	600	22.7	50.2	8.1
^{48}Ti	1000	32.5	109.5	4.5
^{56}Fe	600	13.1	175.1	4.1
Total				*500.0*

Ion	Energy (MeV/n)	Range (cm)	LET (keV/µm)	Dose (mGy)
^{1}H	20.0	0.43	2.59	30.4
^{1}H	23.3	0.56	2.29	6.7
^{1}H	27.2	0.75	2.02	7.4
^{1}H	31.7	0.98	1.79	8.0
^{1}H	37.0	1.30	1.58	8.7
^{1}H	43.2	1.72	1.39	9.3
^{1}H	50.3	2.26	1.23	10.0
^{1}H	58.7	2.99	1.09	10.6
^{1}H	68.5	3.95	0.97	11.1
^{1}H	79.9	5.20	0.86	11.2
^{1}H	100.0	7.76	0.73	27.2

Ion	Energy (MeV/n)	Range (cm)	LET (keV/µm)	Dose (mGy)
^{4}He	20.0	0.43	10.34	**11.0**
^{4}He	23.3	0.57	9.14	**2.1**
^{4}He	27.2	0.75	8.06	**2.2**
^{4}He	31.7	0.99	7.12	**2.3**
^{4}He	37.0	1.31	6.29	**2.5**
^{4}He	43.2	1.73	5.56	**2.6**
^{4}He	50.3	2.28	4.92	**2.7**
^{4}He	58.7	3.01	4.36	**2.7**
^{4}He	68.5	3.97	3.86	**2.7**
^{4}He	79.9	5.23	3.43	**2.7**
^{4}He	100.0	7.81	2.90	**6.1**

Simonsen, L.C., Slaba, T.C., Guida, P., Rusek, A., *Plos Bio.* **18**: e3000669; 2020.

GCR Simulator: Beam Delivery Sequence

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- GCR - continuous shower of protons with interspersed He and sporadic HZE
  - Ordering of GCRsim beams defined to approximate this behavior to the extent possible
- **Frequent delivery of protons and helium**
- **Sporadic heavy ions throughout the sequence**
- **Major components of dose delivered first and last (proton/helium)**

Ion Beam, Energy (MeV/n)

- **(H 1000)**, (He 1000), **(Si 600)**
- (H 20), (H 23), (He 20), (He 23), **(Ti 1000)**
- (He 27), (He 32), (H 27), (H 32)
- (H 37), (H 43), (He 37), (He 43), **(O 350)**
- (He 50), (He 58), (H 50), (H 58)
- (H 68), (H 80), (He 68), (He 80), **(C 1000)**
- (He 100), (H 100), (H 150), (He 150), **(Fe 600)**
- (He 250), **(H 250)**

Simplified GCR Simulator

- **6 ion beams (5 different ions)**
  - Intended for users who do not need the entire GCR spectrum

- Defined for collection of preliminary data, countermeasure screening studies, and initial understanding of mixed-field effects

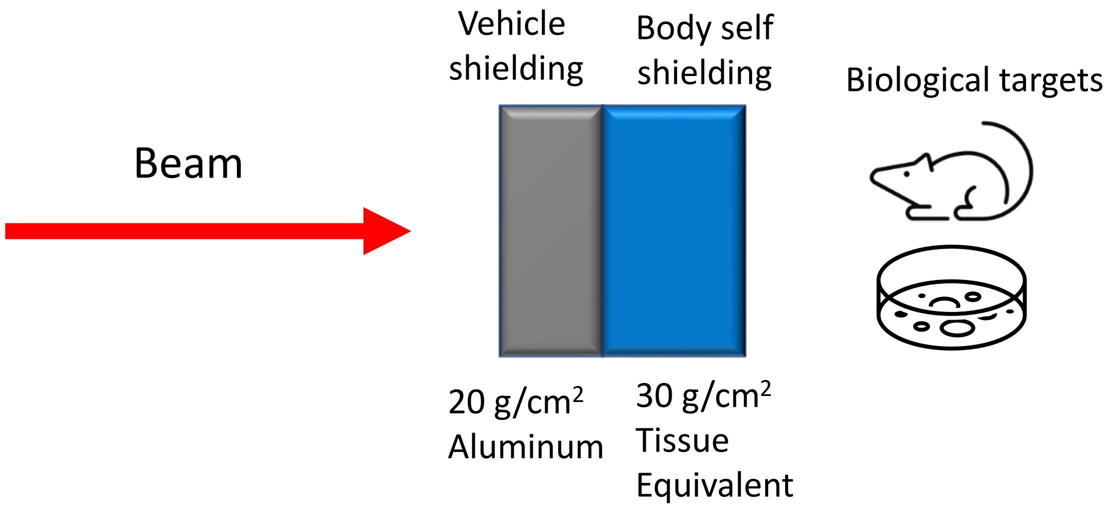
Table 3: Simple GCR Simulator Definition

Ion Species	Energy (MeV/n)	% Contribution to Total Dose	Delivery Order
^{1}H	1000	35	1
^{28}Si	600	1	2
^{4}He	250	18	3
^{16}O	350	6	4
^{56}Fe	600	1	5
^{1}H	250	39	6

Simulation Approach: External Field

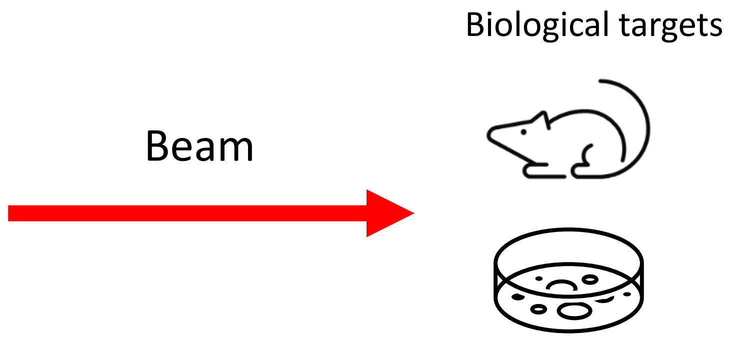
- External free space GCR spectrum with shielding in the beamline
  - Biological target placed downstream from the shield
  - Nuclear reactions produce complex mixed field including neutrons

- Limitations in the external field approach
  - Requires upper energy limits higher than attainable at NSRL for full secondary particle spectrum
  - Substantial mass in beamline
  - Significant dosimetry requirements
  - Difficulty connecting single-beam and mixed-field beam data



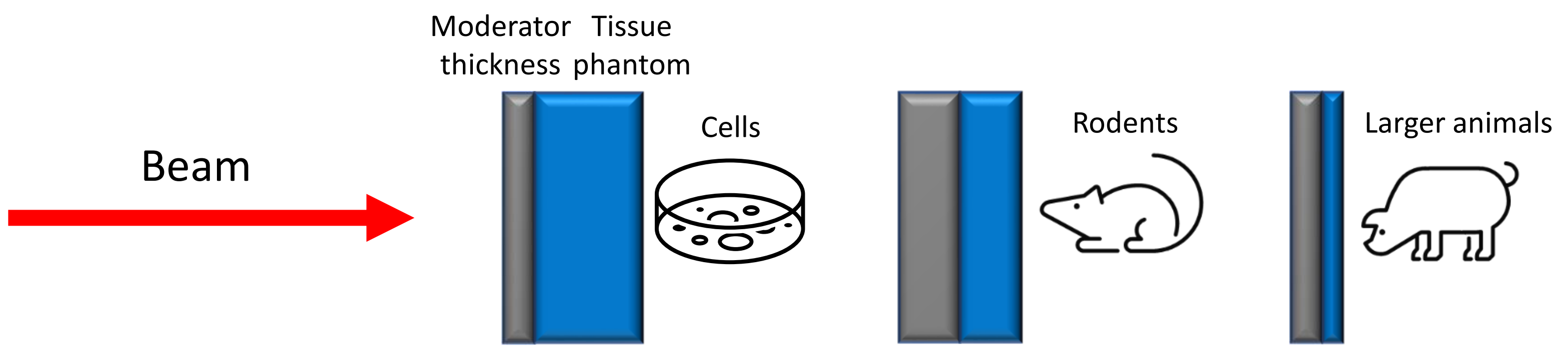
Simulation Approach: Local Field

- Models predict radiation field of the shielded tissue of astronauts in space
- Beams collectively represents the spectrum astronauts are exposed to
- Therefore, no shielding is used
  - Fraction of neutron exposure missing
- **Local field approach was chosen because of its advantages**
  - NSRL's energy limits cover the relevant ranges required for biological experiments
  - Covers 90% of the effective dose vs. 60% for the external approach
  - Current dosimetry system can be used - minimal modifications and cost
  - Enables connection between single-beam and mixed field data
  - Additional animal species beyond mice and rats can be implemented in the design



Simulation Approach: Hybrid

- Combination of external and local approaches
- Beam is optimized with thinner moderator and variable tissue thicknesses inversely scaled to size of the biological sample
- Factors in different body shielding required for different biological targets



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Modeling Advancements from GCRsim

- **Advancements are critical in predictive modeling capabilities to**
  - determine the adequacy of the NSRL GCRsim mixed field definition
  - leverage historical single-ion datasets to test specific hypotheses related to mixed field biological responses

- Several studies have been carried out with various mixed ion protocols

- Predictive models have been developed and are critical for continued progress

Modeling Advancements from GCRsim

- Sachs and colleagues 2018-2020
  - Incremental effects additivity (IEA) model to predict experimental dose-response relationships for mixed-ion exposures
  - Assumes such predictions can be made if corresponding dose-responses for single-beams comprising the mixed-ion composition are known *a priori*
  - **Important approach in the context of cancer risk assessment models, where simple additivity in mixed field exposures is still assumed**

Modeling Advancements from GCRsim

- Slaba, Plante and colleagues (2016-2020)
  - Integrated, multi-scale model using Geant4, RITRACKS, and RITCARD
    - **Geant4** – defines the beam interactions with shielding and/or biological tissue
    - **RITRACKS** – particle fluence as input to describe energy deposition characteristics at a nanometer scale
    - **RITCARD** – track information fed into to describe the cellular damage and repair processes leading to CA formation

- Predicts chromosome aberrations (CA) in cells exposed to
  - Sequential mixed beams
  - Complex radiation fields produced by shielded beam interactions

GCRsim Experimental Studies

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- **Early GCRsim studies considered**
  - Variety of beam and shielding configurations (full and simplified GCR spectrums)
  - Effect of beam order
  - Effect of low and high-LET mono-energetic ion beams
  - Single-ion and multiple-ion exposure

- **Cellular endpoints**
  - Chromosome aberrations
  - Cell survival

- **Animal endpoints**
  - Harderian gland tumorigenesis
  - Lung tumorigenesis and carcinogenesis
  - Gastro-intestinal (GI) tumorigenesis
  - Central nervous system and cognitive function
  - Lifespan studies – neutron vs HZE ion

Dose-rate effects not covered in the workshop

Workshop Discussion

- **Areas of consensus**
  - **Beam composition!**
  - **Beam delivery order!**
  - **Beam standardization (yes, but still allow other mixed fields when justified)**

- **Contradictory results or evidence**
  - Experimental evidence for additivity/synergy are mixed
  - Experimental protocols standardization

- **Questions**
  - Does HZE ion order matter in the full GCR?
  - Is sequential beam irradiation a good model of a true mixed field exposure?
  - Can dose-rate and mixed field questions be decoupled?
  - Should low-energy HZE ions be included?
  - How critical is the neutron component that is currently lacking?
  - The multi-stressor factor and other dependence factors
  - What is the time-dependence of radiation exposure?

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Workshop Findings

- **Participants concurred that**

  1. **Current NASA GCRsim is EXCELLENT!**

  2. **Facility and staff are state-of-the-art**

  3. **Local field approach is reasonable given the practical constraints**
     a. Energy limitations of NSRL
     b. Dosimetry capabilities and requirements (cost)

- Further work is ongoing/needed to optimize the design
  - Hybrid approach to improve neutron aspects
  - Retain spatio-temporal correlations in secondary reaction products

Workshop Findings

- **Ion beam order**
  - Order of ion beam matters in highly simplified beams (e.g. H+Fe)
  - Switching delivery order for heavy ions vs protons showed increased sensitivity
  - Delivering protons first increased sensitivity in endpoints tested
  - <u>Important: ordering seems to be less important in more complex mixed fields</u>

- **Additivity, synergy or antagonism**
  - Synergy: Combination of multiple beams yields a response that exceeds simple additivity
  - Antagonism: Combination of multiple beams is sub-additive
  - <u>Diverse results regarding additivity vs synergy or antagonism for mixed beam exposures</u>

Conclusions

- Virtual GCR workshop was held in December 2020 to assess the current status of NASA's GCR Simulator
- Various aspects of the simulator design were examined
  - Emphasis on GCRsim beam definition
- Consensus was reached that NASA's GCRsim is EXCELLENT
- Further work is needed to optimize the design (hybrid approaches) and address the dose-rate effects
- Workshop details will be published, manuscript in preparation

Acknowledgements

Eleanor Blakely (LBNL)
Marjan Boerma (UAMS)
Richard Britten (EVMS)
Polly Chang (SRI International)
Al Fornace (GU)
Megumi Hada (PVAMU)
Amy Kronenberg (LBNL)
Cynthia Lemere (BWH/HU)
Jian-Hua Mao (UCB)
Greg Nelson (LLUMC)
Rainer Sachs (UCB)
Walter Schimmerling (USRA)
Jerry Shay (UTSMC)
Mike Weil (CSU)

Peter Guida (NSRL-BNL)
Adam Rusek (NSRL-BNL)

Steve Davison (HQ)
Kerry George (JSC)
Janice Huff (LaRC)
Cedric Jackson (NIA/LaRC)
Nafisah Khan (NIA/LaRC)
Nick Meyer (JSC)
Ajitkumar Mulavara (KBR/JSC)
Ryan Norman (LaRC)
Zarana Patel (NIH)
Ianik Plante (KBR/JSC)
Floriane Poignant (NIA/LaRC)
Shirin Rahmanian (NIA/LaRC)
JP Saha (UTSMC)
Lisa Simonsen (LaRC)
Brock Sishc (JSC)
Kelci Skaggs (LaRC)
Tony Slaba (LaRC)
Steve Smith (LaRC)
Jason Weeks (JSC)
Charles Werneth (LaRC)